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P. Stucke et al. (ARC), "SPT-140 High Performance Hall System (HPHS) Development"

AIAA **(Statement A)**

SPT-140 High Performance Hall System (HPHS) Development

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Abstract

The status of the Atlantic Research Corporation's Air Force Integrated High Payoff Rocket Propulsion Technology (IHPRPT) High Performance Hall System (HPHS) contract to develop a 4.5 kW Hall effect thruster system is presented. The SPT-140 system heritage is described, and the members of the HPHS SPT-140 team are introduced. The objectives of the Air Force contract are presented, and the SPT-140 system that has been designed to meet those objectives is described. To meet the IHPRPT goals, the magnetic system has been redesigned to improve thruster efficiency and life requirements. This and other accomplishments in the design and qualification of the SPT-140 system are presented along with the future milestones for the contract.

The HPHS SPT-140 system will provide government and commercial customers an ideal propulsion system for a wide variety of LEO, GEO, and exploratory missions.

Background

In 1992 the joint venture, International Space Technology Inc. (ISTI), was formed to develop and qualify Stationary Plasma Thruster (SPT) systems for use on Western spacecraft. The initial partners included: Space Systems/Loral (SS/L), Experimental Design Bureau Fakel, and the Research Institute of Applied Mechanics and Electrodynamics (RIAME). In 1994, Atlantic Research Corp. (ARC) and Société Européenne de Propulsion (SEP) became ISTI partners. Prior to ISTI's involvement, Fakel had designed, developed and qualified, flight versions of the SPT-50, SPT-60, SPT-70 and SPT-100, and had flown numerous SPT thrusters on Russian satellites[1]. In addition to flight hardware, Fakel developed and built engineering and laboratory models of higher and lower power SPT's ranging from the SPT-30 to the SPT-290.

ISTI set out to qualify a 1.35 kW SPT-100 system for use on Western spacecraft. The ISTI SPT-100 system includes the Fakel SPT-100 thruster (anode and two KN-3b cathodes), the Fakel xenon flow controller, an SS/L power processor and a Moog propellant management assembly. The SPT-100 system qualification program was a formal process based on Mil-Std 1540 which included vibration, shock, and thermal tests, as well as two 7,000+ hour life tests[2,3], and a 1,000 hour integrated system test[4]. After extensive testing and electronics development, the system, was successfully

qualified in 1996[5,6], and is now baselined for use on Stentor, Cyberstar and Astra 1K satellites.

In 1996, after successful qualification of the SPT-100 system, ISTI began funding design and development activities at Fakel and RIAME to develop the SPT-140 thruster to meet the emerging market for high power, high efficiency Hall thrusters. Prior to award of the Air Force IHPRPT contract, over ten engineering and laboratory SPT-140 models had been designed and fabricated at Fakel. This included a thorough testing program; the matrix of pre-contract development tests is shown in Table 1.

Table 1 - Pre-contract SPT-140 Testing

Number of Tests Conducted	Type of Test
10	Parametric
18	Firing
4	Thermal vacuum
4	Dynamic environment
6	Magnetic
1	Electrical design
7	Cathode (includes two short life tests)

The IHPRPT contract formally began on September 15, 1997 and will run through December 31, 2001.

High Performance Hall System Team

The SPT-140 High Performance Hall System team is a unique partnership of leading US and Russian government, industry and academic institutions. Atlantic Research Corporation is the prime contractor for the US Air Force: the team members are described below:

Government

- US Air Force Research Laboratory: Program funding / oversight, life testing

Industry

- Atlantic Research Corporation: prime contractor
- International Space Technology Incorporated: systems technical lead
- Experimental Design Bureau Fakel: design, manufacture and acceptance test of SPT-140 thruster (anode and KN-15 cathode) and SPT-140 Xenon Flow Controller
- Cosmotech: on-site ISTI representation at Fakel
- Space Systems/Loral: Power Processor Unit design and fabrication; system engineering

Academic

- Moscow Aviation Institute, RIAME thruster conceptual design and materials qualification
- University of Michigan: thruster plume analysis

The US Air Force Research Laboratory is and has been a leader within the government promoting advanced propulsion for spacecraft. The industrial team members cited above are directly responsible for the design, manufacture, test, and successful flight and on-orbit operation of every Hall effect thruster that has been launched to date. RIAME and the University of Michigan have leading technical experts and extensive facilities for testing and evaluating Hall thrusters.

Call Keith ?

IHPRPT Objectives

The IHPRPT program is a coordinated DoD/NASA/Industry effort to develop revolutionary and innovative technologies by the year 2010 that will permit a doubling of rocket propulsion capabilities over 1993 state-of-the-art technology. The IHPRPT program is structured in three phases and three mission application areas to achieve predetermined measurable increases in all rocket technology capabilities. The HPHS program addresses the following IHPRPT Phase 1 goal for electrostatic propulsion under the spacecraft propulsion mission area:

- Improvement of propulsion system total impulse over propulsion system wet mass by 20%

This goal supercedes the previous goals of increasing propulsion system efficiency and mass fraction each by 15%; baselines associated with

the goals were also modified. While this contract was negotiated under the previous goal, attainment of the current IHPRPT goal is supported by the following contract technical objectives:

- Increase thruster energy conversion (thrust efficiency) by 10%
- Increase thruster life by 500%
- Increase power processor unit efficiency by 3%
- Decrease hardware costs by 0 - 40%

Achievement of these objectives will lead to system payoffs including increased mission life, payload mass fraction, repositioning ability and decreased launch costs.

High Performance Hall System Description

Integrated System

The HPHS consists of four primary components: the SPT-140 thruster (anode and KN-15 cathodes); Xenon Flow Controller (XFC); Power Processor Unit (PPU), which includes a Thruster Selection Unit (TSU); and the Propellant Management Assembly (PMA). The relationship between these components is shown in Figure 1.

Thruster

The HPHS SPT-140 design draws upon the heritage of the Fakel SPT-100 and KN-3b cathode which has flown 32 times on Russian satellites with a 100% success rate, and has been fully qualified for use on Western satellites. The SPT-100 has been described previously[7,8]; general operation of the SPT-140 is similar to the SPT-100.

Key SPT-140 thruster parameters are presented in Table 2.

Table 2 HPHS SPT-140 Thruster Specifications

Thruster Parameter	Specification
Power	4,500 W
Voltage	300 V
Total Impulse	5.85×10^6 N-s
Specific Impulse	1770 s
Thrust	290 mN
Efficiency	55%
Mass (anode + 2 cathodes)	6.8 kg

The HPHS SPT-140 thruster consists of the anode block, which has three primary elements - anode/gas distributor, discharge chamber, and the magnetic path; and two KN-15 cathodes. Figure 2 presents the HPHS SPT-140 anode block. The neutral xenon propellant is evenly distributed within the annular discharge chamber by the anode ring. The discharge chamber is made of Borosil ceramic, which insulates the thruster body from the plasma formed by the xenon propellant. The magnetic path consists of magnet coils, a magnetic pole and a magnetic base. The HPHS SPT-140 magnet coils are powered by a separate power supply. This will provide additional flexibility for thruster operating points, and the requirement can be accommodated with modifications to the magnet bias supply implemented in earlier PPU's.

The KN-15 cathode is a derivative of the high power KN-50 (50 Amp) cathode that was developed by Fakel for the SPT-200. However, the KN-15 also uses many of the same fully qualified processes of the KN-3b cathode that has been successfully qualified, life tested and flown with SPT-100 thrusters. It contains a LaB_6 emitter, heating coil, thermal screens and an ignitor. LaB_6 was chosen for the emitter material because of its ability to withstand a variety of environments. These cathodes require no special handling or environment on the ground, and no special on-orbit outgassing procedures. While no Fakel cathodes have failed in operation, it is typical to use two cathodes for redundancy, and that is the baseline of the HPHS SPT-140.

Xenon Flow Controller

The primary functions of the XFC are: provide fully redundant flow paths to the anode block, minimize xenon loss between firings, switch flow between either of the two cathodes, divide the flow to achieve the appropriate mass flow ratio

Table 3 – Power Processor Specifications

	First Generation 42V PPU-100	Second Generation 100V PPU-100	Third Generation 100V PPU-140
Input Voltage	39 V min 45 V max	95 V min 105 V max	95 V min 105 V max
Command and Telemetry	0-5 V analog TTL 28 V pulse	485 serial bus	485 serial bus
Power Range	800 W min 1,500 W max	800 W min 1,500 W max	2,000 W min 5,000 W max
Mass	7.5 kg	6.8 kg	13.7 kg
Efficiency	93-94%	93-95%	94-96%
Reliability	0.97	0.945	0.94
Envelope	11.4"x9.8"x5.8"	11.4"x9.7"x5.8"	23.0"x11.0"x5.8"
Qualification Status	Qualified 12-96	Expected Qualification 8-98	Expected Qualification 12-99

between the anode and the cathode, provide the ability to make fine flow control adjustment to maintain constant discharge current, and throttling.

The XFC controls the flow rate of xenon through a simple thermal throttle system which adjusts the flow via a closed loop controller in the PPU that regulates heater current to the thermothrottle.

The SPT-140 XFC is closely based on the heritage of the fully qualified and flight-tested SPT-100 XFC. Minor modifications were made to the SPT-140 XFC to properly divide flow, and throttle at the higher flow rates required by the SPT-140 thruster.

Figure 3 shows a block diagram of the SPT-140 XFC.

Power Processor Unit

The PPU-140 powers, monitors, and controls the SPT-140 thruster and xenon flow controller. It is a third generation PPU that builds off of SS/L's successful PPU-100, which was qualified with the SPT-100 thruster in 1996.

The power processor consists of the following supplies: anode supply, which provides the primary discharge power; a separate magnet supply; cathode heater supply; ignitor supply; and the XFC driver, which controls the XFC solenoid valves and thermothrottle. The PPU-140 is designed for a 100 V bus and is compatible with an RS485 serial data interface. It is self-sequencing at startup and all outputs are current limited.

The ignitor, flow control and valve driver are the same as the corresponding modules on the PPU-100. The discharge supply has been changed to three 1,500 W supplies in parallel, the heater supply has been changed to allow higher power and the magnet supply has been changed for higher voltage operation.

The PPU also incorporates a Thruster Selection Unit (TSU) which allows the output power to be routed to either of two SPT-140's and switch to either of the two cathodes on each thruster.

Table 3 lists key parameters for the third generation PPU-140 and the first and second generation PPU's developed for the SPT-100.

Propellant Management Assembly

The propellant management assembly (PMA) is shown conceptually in Figure 4, and is based on the PMA that was successfully qualified with the SPT-100. The SPT-140 requires a higher flow rate than the SPT-100, but the critical components of the heritage SPT-100 PMA have already been validated at the higher SPT-140 flow rates.

Accomplishments

As discussed previously, the objectives of the HPHS contract are: increased thruster efficiency and life, increased PPU efficiency, and decreased system cost. Therefore, the focus of the design and development activities has been technological improvements to the thruster and PPU, while heritage components are used to the fullest extent possible to provide flow control and propellant management. Achievement of these objectives requires an aggressive design and technology development program in both the US and Russia, validated with extensive modeling and testing throughout the process.

Design Philosophy

The SPT-140 thruster design and development process employs the proven Hall thruster development technique pioneered by Fakel with the SPT-70 and SPT-100 programs. This technique involves iterative development and testing of laboratory model thrusters followed by higher level engineering model (EM) units. Individual EM units are subjected to dynamic, thermal and performance testing to determine suitability of design features and iterative improvements are made. By using multiple units, tests can be conduced in parallel thus reducing development time and substantially reducing risk. Key results and features from multiple EM units are then evolved into higher level EM units and again put through testing. SPT-140 development was enhanced by design techniques such as computer aided thermal, structural and magnetic modeling, thus reducing development time.

When the results of EM testing are satisfactory, demonstration model (DM) hardware is fabricated and subjected to formal acceptance testing, followed by a partial life test. When the decision is made to proceed with fabrication of the DM hardware, most risk has already been mitigated. Testing of the DM unit permits final verification of the design with regards to performance and life and contributes to further reduction in risk for the formal qualification hardware testing.

Design Improvements

The HPHS SPT-140 thruster, incorporates many of the qualified parts, materials, and processes of the SPT-100, but numerous improvements to increase thruster performance and life, and reduce cost have been incorporated, as described below.

Performance

To meet the contract efficiency objective, the magnetic system of the SPT-140 was enhanced. Additional magnet coils were added (Figure 2). Modifications of the length and position of the magnetic screens and the height of the coil winding were incorporated into the design of the magnetic path to tailor the shape of the magnetic field to achieve higher efficiency.

As shown in Figure 5, the pre-contract SPT-140 engineering model thrusters achieved roughly 50% efficiency. To increase the efficiency, a rapid design and development cycle was initiated involving both Fakel and RIAME. Six Engineering Model (EM) model thrusters were designed, fabricated and tested with various configurations of the magnetic path, two variations of anodes, and with and without additional magnet coils. Each modification was tested at 300 V and 350 V and power levels from 3,000 to 5,000 W (see Figure 6). The result of this rapid prototyping was the EM5 model thruster that achieved 55% efficiency in April of 1998, a 5 percentage point improvement in efficiency in five months. This configuration was used as the basis of the Demonstration Model (DM) thruster fabrication.

Life

The erosion of the ceramic discharge chamber was simulated using the model previously developed for the SPT-100[9]. Based on this model and initial testing, it was determined that in the early SPT-140 engineering model designs, the outer ring of ceramic was operating at a significantly higher temperature than the SPT-100. This would have led to an unacceptable erosion rate, and consequently much reduced lifetime. A series of experiments were conducted based on the results of the SPT models. The magnetic path components were changed to alter the shape of the magnetic field and lower the temperature of the outer ring of the ceramic. In addition, the configuration of the discharge chamber at the exit plane was changed to increase the life of the thruster.

Mass
The mass of the thruster was reduced from an initial mass of over 8 kg for early engineering models to 6.8 kg for the DM thruster. This was accomplished by iterating and testing the magnetic components to remove mass from the magnetic system while still meeting performance specifications.

In addition to the performance enhancing features described above, a number of improvements were made to increase the reliability of the thruster or reduce the cost. The anode attachment to the discharge chamber was changed to make it easier to machine and more robust to vibration loading. The number of attachment points were increased from the SPT-100 design to ensure the larger anode will survive launch vibration loading. The number of hermetic welds in the cathode was reduced to lower manufacturing cost and increase reliability. Additional dielectric insulation was added to key points to increase the robustness and reliability of the thruster. The wiring scheme of the thruster was simplified to reduce the number of solder joints, which will reduce the assembly labor and increase reliability.

Contract Studies
The HPHS contract also calls for several studies to be accomplished in the US by ARC and ISTI, these include:

(1) A Utility Analysis to determine the optimal power and voltage for various mission applications including LEO reboost, GEO orbit topping, and subsequent north south station keeping. Parameters considered in the analysis included: thruster mass flow, voltage, spacecraft wet mass, fraction of orbit raising due to electric propulsion, launch vehicle GTO, thruster cant angles, S/C lifetime, S/C manufacturing time, discount rate, revenue ramp up time, and S/C cost per kg dry mass. The report on this Utility Analysis Study has been completed and submitted to the US Air Force.

A key result of the Utility Analysis is presented in Figure 7, which presents the economic benefit of SPT's as a function of orbit raising duration. Relative to the state-of-the-art SPT-100, the HPHS SPT-140 thruster benefits missions by using power more effectively due to its higher unit thrust and higher efficiency. The Utility Analysis quantified this benefit in terms of spacecraft "equity value" for a range of launch vehicle parameters and costs, time value of money, and other parameters as discussed above. As shown in Figure 8, the Utility Analysis found the economic benefit of the SPT-140 with respect to the SPT-100 to be in the range of 5 to 10 million dollars per spacecraft, for an orbit raising duration of zero to 60 days.

FIGURE 7?

(2) A US Fabrication Feasibility Study to demonstrate the feasibility of fabricating and qualifying the SPT-140 in the US in the event of a disruption in the Russian source of supply. Tasks include identifying all data necessary for thruster fabrication and qualification, identifying all resources required for production, and including the above information in a manufacturing escrow package. This feasibility study is currently underway.

Milestones

To date, there has been a successful thruster PDR in December of 1997, the first IHPRPT semi-annual review in April 1998, completion of the Utility Analysis in May of 1998, and completion of the DM thruster fabrication in June 1998. Future milestones include the following:

Thruster

Table 4 - Thruster Milestones

Milestone	Date
Start life test of DM	August 1998
Thruster CDR	November 1998
QM-1 thruster delivery	February 1999
QM-2 thruster delivery	April 1999
Start long duration life test of QM-1	July 1999

Prior to life testing, the DM unit will undergo full acceptance testing in accordance with Table 5 at the qualification loads. The DM life test will validate the erosion and performance models, which will provide additional assurance that the Qualification models will pass qualification testing. The DM unit will also be used for the plume ion energy tests in the US.

The thruster CDR is positioned to allow lessons from the DM fabrication and testing as well as results of the thermal and structural modeling to be taken into account prior to QM fabrication. The overall goal of this iterative design and development process being to retire as much risk as possible prior to the extended life test in July 1999.

The QM-1 thruster will be fabricated for the USAF and will undergo the full qualification program in Table 6. A second thruster, the QM-2 will also be fabricated and will undergo acceptance testing in accordance with Table 5.

Table 5 - Thruster Acceptance Tests

#	Test
1	Examination
2	Xenon Flow Controller Proof Pressure
3	Xenon Flow Controller Leakage
4	Xenon Flow Controller Functional
5	Reference Performance
6	Thermal Cycling
7	Random Vibration
8	Xenon Flow Controller Leakage
9	Xenon Flow Controller Functional
10	Reference Performance
11	Physical Examination

Table 6 - Qualification Tests

#	Test
1	Acceptance Tests (Table 5)
2	Sinusoidal Vibration
3	Random Vibration
4	Shock
5	Xenon Flow Controller Functional
6	Xenon Flow Controller Leakage
7	Reference Performance
8	Thermal Cycling
9	Xenon Flow Controller Functional
10	Xenon Flow Controller Leakage
11	Reference Performance
12	Thruster Fire Tests
13	Life Tests
14	Reference Performance
15	Xenon Flow Controller Functional
16	Xenon Flow Controller Leakage
17	Xenon Flow Controller Burst Pressure
18	Radiographic Examination
19	Disassembly and Inspection

Power Processor

Table 7 Power Processor Milestones

Milestone	Date
Breadboard fabrication	August 1998
PDR	October 1998
Brassboard fabrication	January 1999
CDR	April 1999
EQM-1 fabrication	August 1999
EQM-2 fabrication	October 1999

Table 7 lists several relevant PPU milestones.

Integrated System

Table 8 System Integration Milestones

Milestone	Date
Thruster Thermal Test	April 1999
PPU Thermal Test	January 2000
200 hr. Integrated System Test	April 2000

Key system integration milestones are listed in Table 8. After system integration design and fabrication, the ARC team will analyze the

system specific cost (dollars per Newton-second) and compare that with the contract objective of up to 40% reduction in cost. The ARC team will also analyze the capability of the system with respect to the contact goals and report on mission payoffs based on the work performed under the Utility Analysis.

A final integrated systems test will validate all subsystem interfaces and margins over a range of operating conditions.

Conclusions

The objective of the HPHS SPT-140 contract is to develop and qualify an advanced 4.5 kW Hall propulsion system that fulfills the IHPRPT requirements and meets the needs of a variety of government and commercial missions. To achieve this goal, the efficiency of the thruster has been increased through advanced design of the magnetic components, the service life will be qualified in a long duration life test, the power processor efficiency will be increased by 3%, and production and use costs will be decreased by up to 40%. This contract will develop a propulsion capability that is unparalleled in the world in its combination of leveraging of fully qualified, flight proven processes, high power, high efficiency, long life and low cost. The HPHS SPT-140 will provide government and commercial customers an ideal solution to a wide variety of LEO, GEO and exploratory missions.

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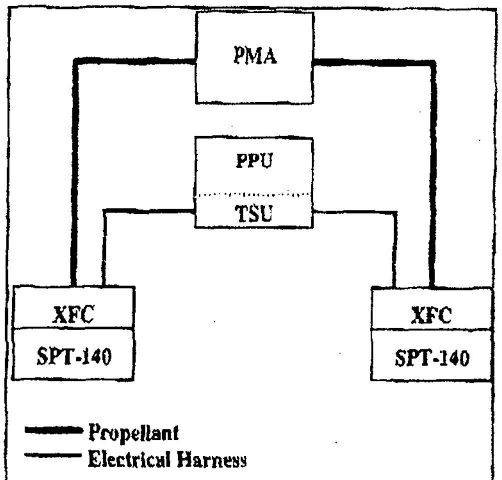

Figure 1 - SPT-140 System Block Diagram

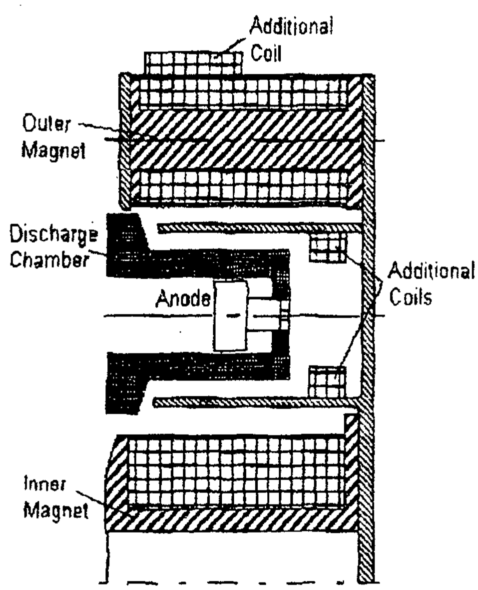

Figure 2 – SPT-140 Anode Block

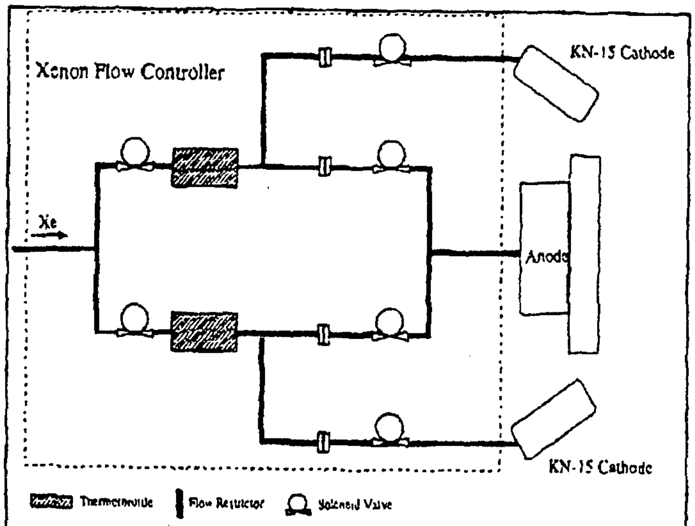

Figure 3 - XFC Block Diagram

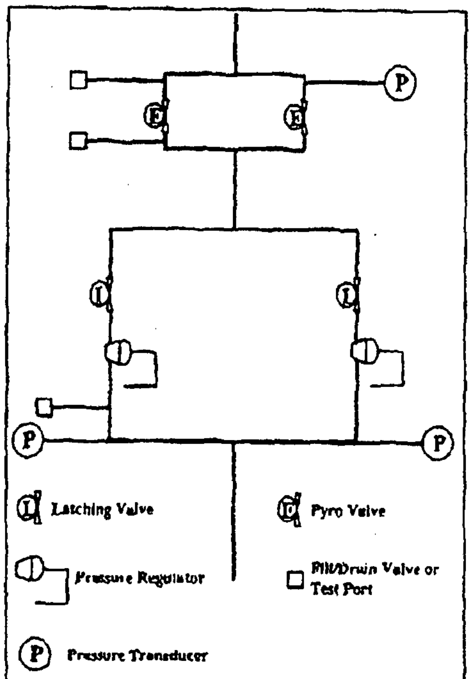

Figure 4 - PMA Block Diagram

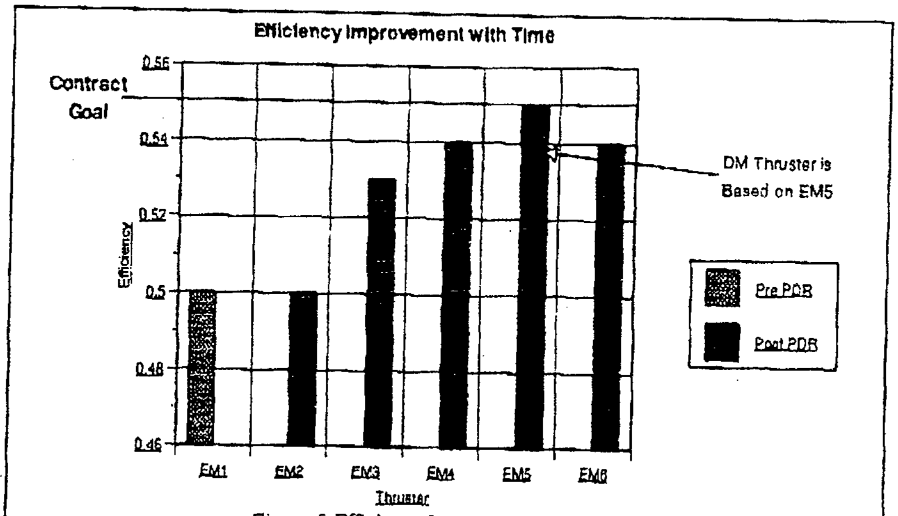

Figure 5 Efficiency Improvement Post PDR

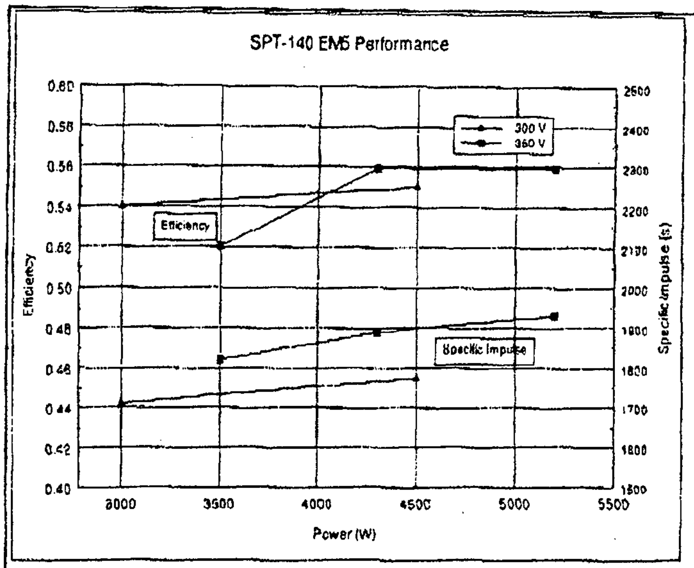

Figure 6 - SPT-140 EM performance

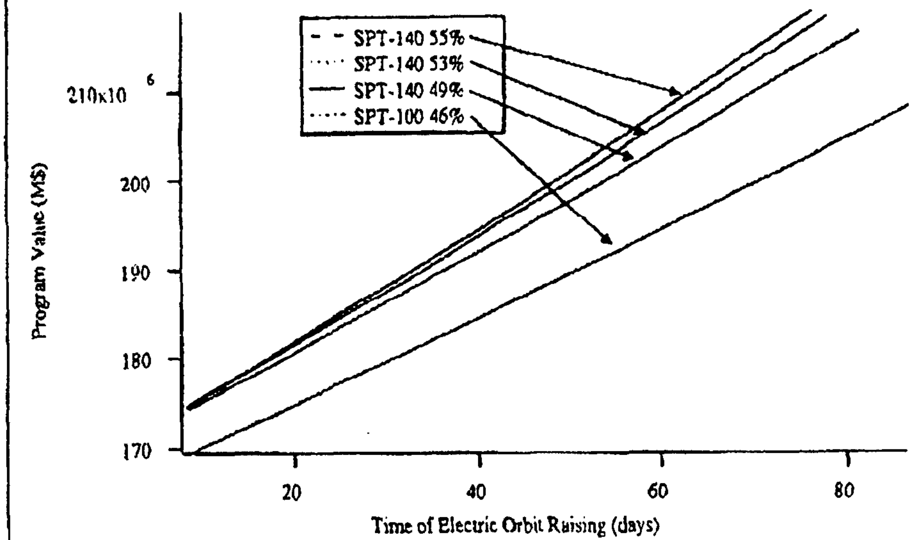

Figure 7 – Economic Benefit of HPHS Thruster